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1.

## INTRODUCTION

The TASC Magsat Investigation covers an area in the eastern Indian Ocean which contains several major bathymetric and tectonic features (Fig. 1-1). The overall objectives of this investigation are:

- Determination of the optimum resolution of Magsat anomaly maps of the study region.
- Production of magnetic anomaly maps from Magsat data covering the study region (0-50 deg S, 75-125 deg E).
- Comparison of Magsat and satellite altimeter (geoid undulation) data in this area, and quantification of their relationships.
- Interpretation of the Magsat data using satellite altimeter and other geophysical data in order to determine the origin and sources of the observed magnetic anomalies.

The investigation area contains of a variety of tectonic and physiographic features shown in the figure.

The investigation during this quarter focused in four areas:

- **ANALYSIS OF THE BROKEN RIDGE**  
A higher resolution anomaly map of the Broken Ridge area (2 degree dipole spacing), was produced and reduced to the pole, using quiet time data for this area. This map was compared with equally scaled maps of gravity anomaly, undulation, and bathymetry. A preliminary analysis of the geophysical structure of the Broken Ridge is in this report.

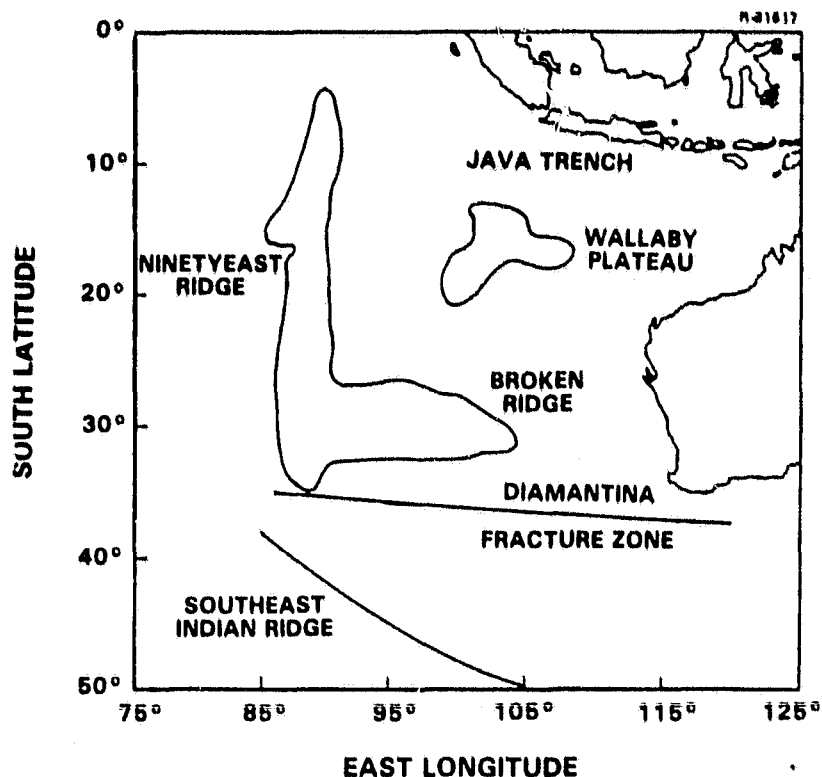


Figure 1-1 Investigation Area Showing Major Tectonic Features

- **COMPARISON OF AREA-WIDE MAPS**  
ESMAP results were compared with a NASA Magsat map derived by averaging data in two-degree bins. The 2 by 2 degree map of the Earth's crustal anomaly field was provided by NASA. The portion of this data corresponding to this investigation was extracted and compared with preliminary ESMAP results.
- **MAGSAT SURVEY SIMULATION**  
A survey simulation was developed to model the accuracy of Magsat anomaly maps as a function of satellite altitude, instrument noise level, external field noise model, and crustal anomaly field model.

Before proceeding with the final anomaly map production and analysis of the entire investigation area, a preliminary local analysis is desirable using gravity and magnetic

anomaly data supported with bathymetry and undulation data. The area chosen for this local analysis includes the Broken Ridge, an area of special geophysical interest due to the associated magnetic high in the investigation area. The Broken Ridge may consist of submerged continental crust giving rise to this magnetic high. Some preliminary geophysical analysis using the Broken Ridge data was accomplished to further our understanding of the techniques to be used in this investigation.

2.

ANALYSIS OF BROKEN RIDGE

Maps were produced (plotted at the same scale, with 1 deg grid spacing) for several geophysical parameters in the Broken ridge area: 1) A magnetic anomaly map with approximately 2 degree dipole spacing (Fig. 2-1). This map is reduced to the pole and shows evidence of the grid of dipoles (ripple effect). 2) Bathymetry with 250 meter contours (Fig. 2-2). 3) Gravity anomaly map with 2.5 mgal contours (Fig. 2-3). 4) Undulation map with 2.5 meter contours (Fig. 2-4).

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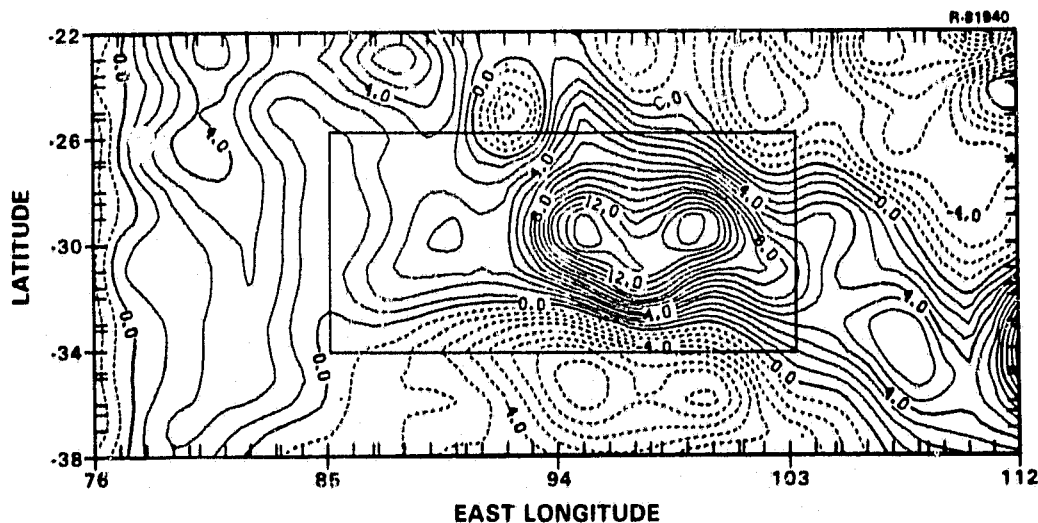


Figure 2-1 Detailed Magnetic Anomaly Map for the Broken Ridge. Anomaly values outside of inset box are contaminated with edge effects. Contour interval: 1 nT.

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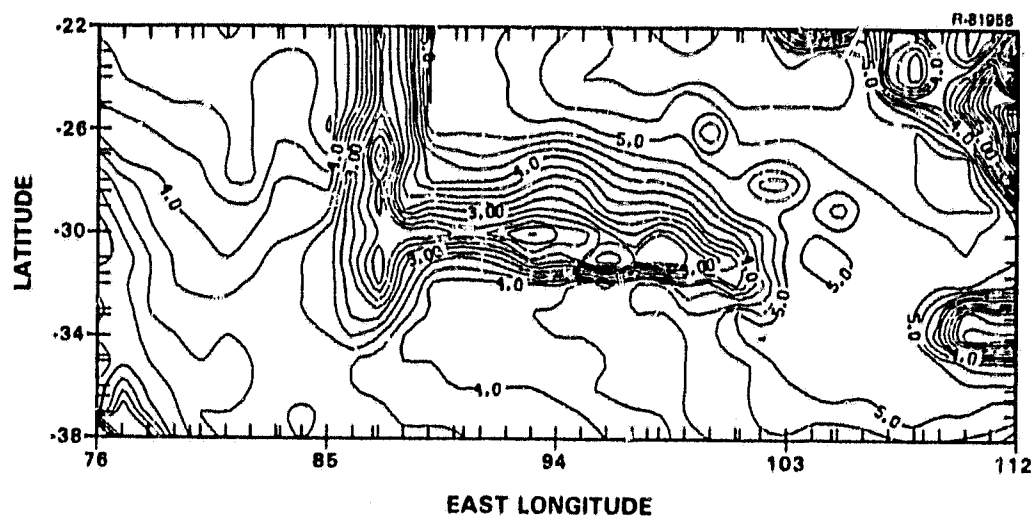


Figure 2-2 Bathymetry for Broken Ridge.  
Contours are in 250 meter steps.

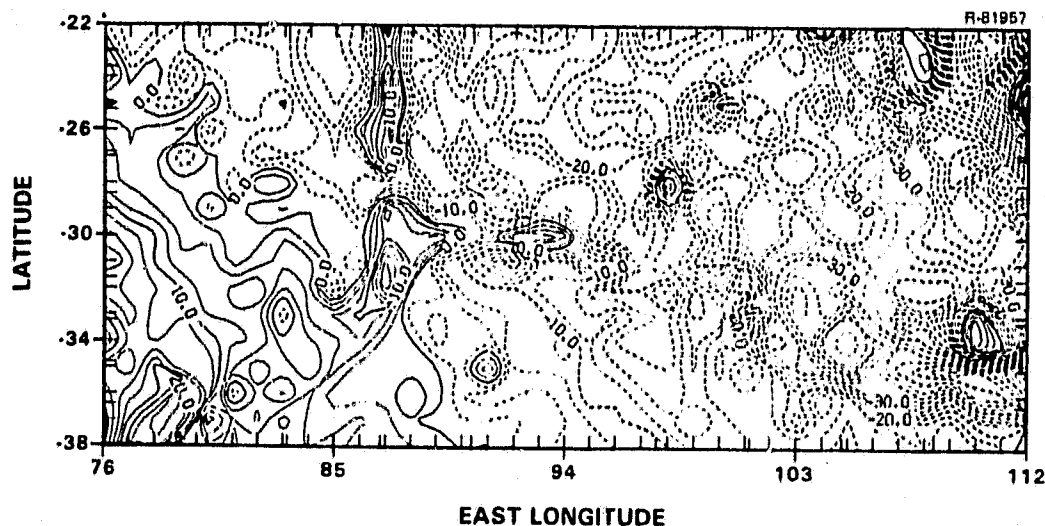


Figure 2-3 Map of Gravity Anomalies for Broken Ridge.  
Contours are in 2.5 mgal steps.



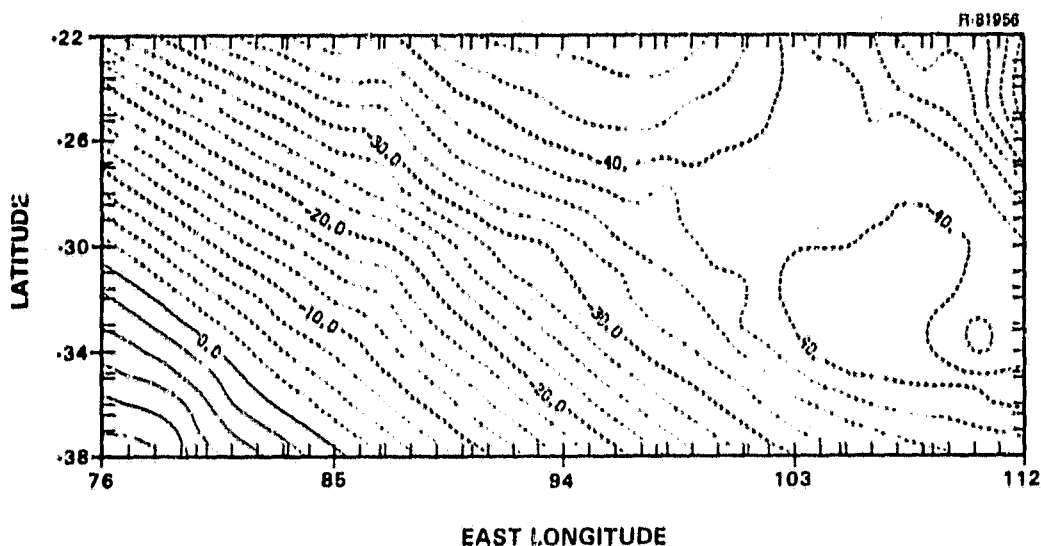
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Figure 2-4 Map of Geoid Undulation for Broken Ridge. Contours are in 2.5 meter steps.

A magnetic high is evident in the magnetic anomaly map at the eastern (but not the western) end of Broken Ridge, with evidence of a low just south of the high. There are two possible interpretations:

First, the magnetization values of the modeled dipoles do not depend on neighboring dipoles: This interpretation assumes an induced model for the crustal magnetization, that reduction to the pole rotates the dipoles exactly to a vertical position, and is typical of interpretations for this type of data (e.g., Ref. 1). The Broken Ridge, having excess mass and/or higher magnetic susceptibility relative to the surrounding area, gives rise to a magnetic high caused by magnetic induction. The magnetic anomaly feature south of the Broken Ridge, while lower than the magnetic anomaly north of the Broken Ridge, is unrelated to the Broken Ridge itself and is due to the variation in the geology of the plate surrounding the Broken Ridge (e.g., Ref. 2). This model does not require that the zero anomaly contour be accurately placed.

Second, the magnetization values of the modeled dipoles may depend on neighboring dipoles: This interpretation extends the interpretation above to attempt to explain the magnetic low south of the Broken Ridge in terms of a single magnetic and geologic structure at the Broken Ridge, thus linking it to the magnetic high. This model for the eastern end of Broken Ridge consists of model dipoles in the crust, generally inclined to the north. The direction of the inclined dipoles probably represents either the difference in orientation between the present field and the remanent field from the time of formation of the Broken Ridge, a geologic structure dipping to the south, and/or an error in reduction to the pole. These model dipoles give rise to both the magnetic high over the Broken Ridge and to the low just south of the Broken Ridge. This model requires that the zero contour line is approximately correct for the crustal anomaly field, i.e. that the low is negative on an absolute scale and not just with respect to the regional mean.

It is important to note that the original Magsat data was preprocessed by removing a mean and ramp for each Magsat track. These were removed to minimize effects of external currents and fields. If there were a regional trend in the crustal anomaly field over the entire investigation area, inclined in the same general direction as the Magsat tracks (approximately North-South), this trend would also be removed. If this were the case, the relative anomaly magnitude between small features in the North and small features in the South would be altered. For example, if the actual crustal anomaly field were tilted to the north, removal of this trend would enhance negative features toward the south, and positive features toward the north. The existence of such a systematic error has not been established, but could give rise to apparently inclined dipoles in maps reduced to the pole.

Visual inspection of the various maps results in the following observations:

- The eastern end of the Broken Ridge does not correlate with a gravity high.
- The western end of the Broken Ridge, connecting with the Ninetyeast ridge is associated with a gravity high, and possibly a small magnetic high. This connecting part does not have the same magnetic properties as the eastern end of the Broken Ridge.
- The southern part of the Ninetyeast ridge is not associated with a major magnetic anomaly, but is associated with a gravity high.

A preliminary conclusion based on these observations suggests that the Broken Ridge consists of two areas with differing crustal properties. The western portion shares similar gravity and magnetic anomaly properties with the Ninetyeast Ridge, and thus may be part of the same geological feature. The eastern portion of the Broken Ridge appears to be a separate geological entity from the western section and the Ninetyeast Ridge. This conclusion is subject to revision after an analysis of the magnetic anomaly map, yet to be produced, for the entire investigation area, and comparison with other geologic data.

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3. ANOMALY MAP COMPARISON: ESMAP VS 2 X 2 DEGREE AVERAGE

From NASA, TASC received a digital version of the Magsat world-wide  $2 \times 2$  degree scalar anomaly map averaged at satellite altitude. This data is plotted for the investigation area in Fig. 3-1. A new ESMAP run of all data points in all the available tracks (495) with 121 dipoles produced the preliminary map in Fig. 3-2. Although slight variations are

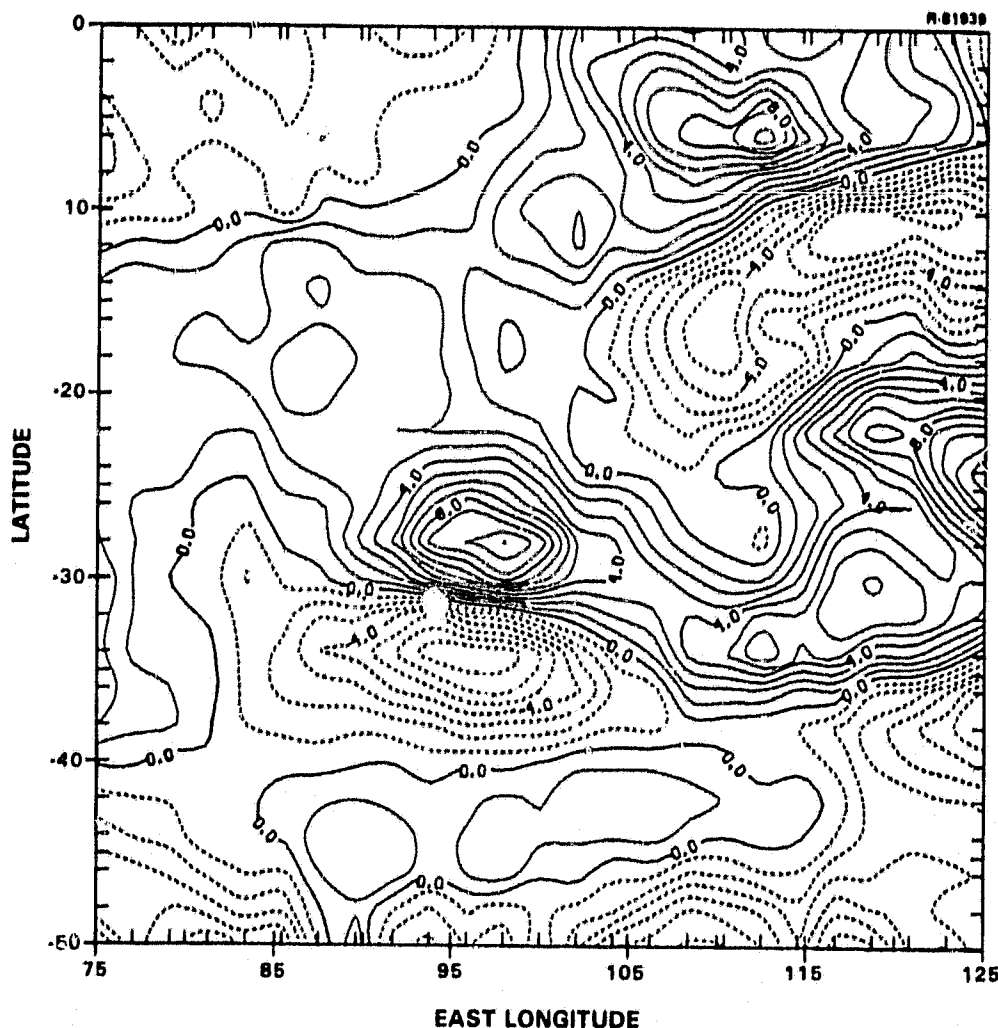


Figure 3-1 NASA Crustal Magnetic Anomaly Map, at  
Satellite Altitude,  $2^\circ \times 2^\circ$  Grid.

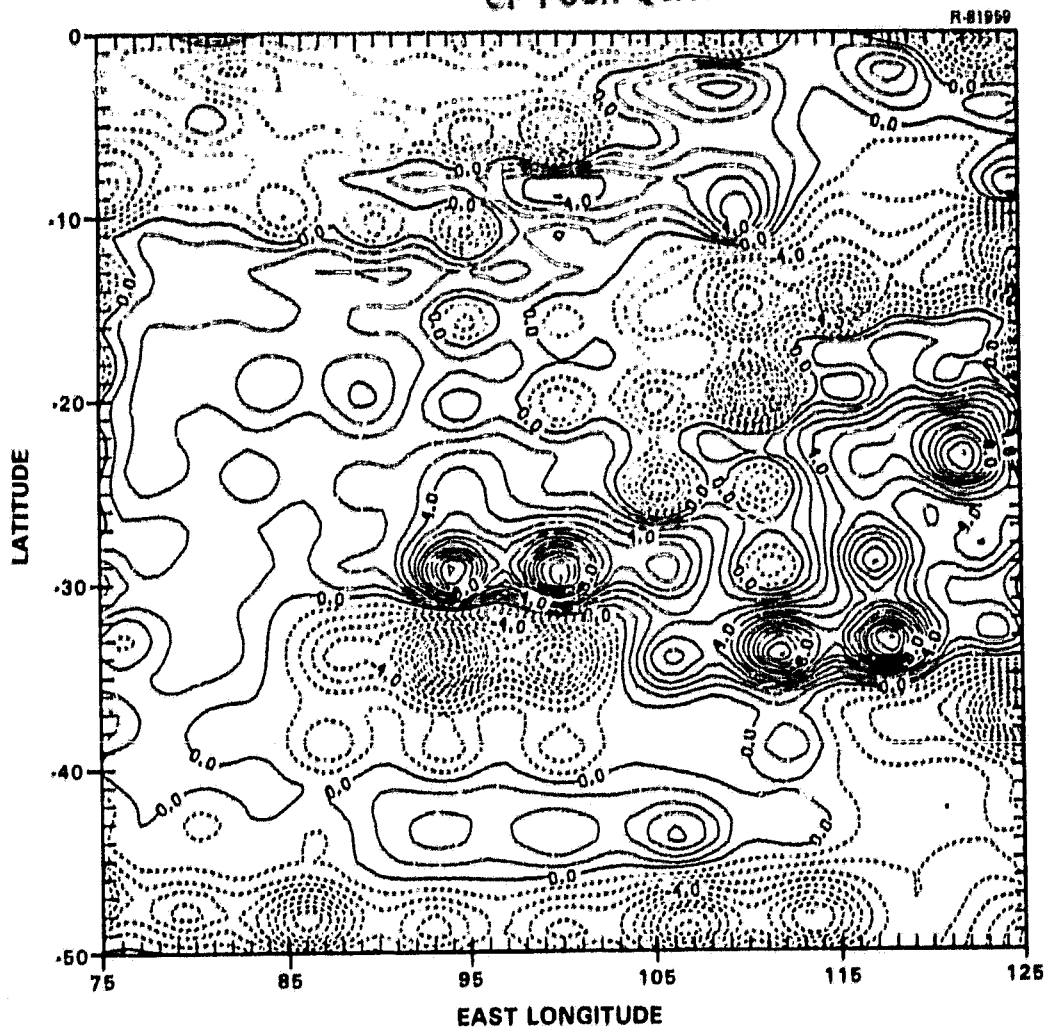
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Figure 3-2 Crustal Magnetic Anomaly Map Derived from 121 Equivalent Source Dipoles. Map is plotted at 350 km altitude, not reduced to pole.

observed from the previous version in Ref. 3, the new map is considered more accurate as it is based on 30% more Magsat data. Figures 3-1 and 3-2 compare reasonably well (visually) with  $2 \times 2$  degree anomaly map relative to the locations and magnitudes of major anomaly features. The advantages of the map in Fig. 3-2 over Fig. 3-1 are that the former corrects for the altitude of the observation points, can be computed at any altitude, yields a grid of magnetization parameters (useful crustal geophysical parameters), and can produce an anomaly

field reduced to the pole. The disadvantage of the equivalent source map in Fig. 3-2 is that the dipole locations are very evident (the ripple effect seen with approximately 4-degree dipole spacing, also seen with 2-degree spacing in Fig. 2-1) and contaminate the resulting ESMAP anomaly map.

The process of fitting gridded dipoles to the Magsat data, then computing an anomaly field from the dipoles results in the mapping of two useful geophysical quantities: crustal magnetization (computed from the dipole moments) and crustal magnetic anomalies at satellite altitude. A small dipole spacing (e.g., 1 degree) should result in an accurate anomaly map at satellite altitude, relatively free of the "ripple" effect and high frequency noise (e.g., greater than 0.01 cycles/km), but gives rise to a larger standard deviation in the estimate for the magnetization parameter accompanied by spurious oscillations with a wavelength of 2 dipole spacings (Ref. 5). A large dipole spacing (e.g., 4 degree) should result in stable and accurate estimates for crustal magnetization (with good crustal models) but will yield inaccurate anomaly maps with oscillations (the ripple effect) and higher uncertainties in the anomaly values. The tradeoff in choosing the optimal dipole spacing is between higher accuracy and stable solutions for the magnetization parameters and the anomaly values. The optimal dipole spacing has not yet been determined, but the problem is typical of those investigated at TASC (e.g., optimum order selection in auto-regressive modeling). The analytic method described by McLeod (Ref. 4) may also be of use in this problem.

## 4.

MAGSAT SURVEY SIMULATION

Based on experience with analysis of gravity survey data, TASC developed a survey simulation to estimate the accuracy of various satellite survey configurations for extracting the crustal magnetic anomaly field. The analysis is performed in the two-dimensional spatial frequency domain, taking into account the geometry of the survey (e.g., orbit inclination, altitude) and the power spectra of: the external noise, the instrument noise, and the anomaly field to be derived from the noisy observations. In addition to the effects of the external field and the instrument noise, the analysis takes into account the errors caused by aliasing and the pattern of track coverage. However, in the current software, a constant altitude (circular orbit) has been assumed.

The simulation requires statistical models for the crustal anomaly field, the external field noise, and the instrument noise. For the results shown here, the instrument noise was modeled as white noise with an rms of 0.3 nT (Ref. 6, Fig. 12). The external noise power spectrum was modeled according to a formula based on observatory data (Ref. 7):

$$P_z = \left(3.68 \times 10^{-5}/f^2\right) \exp (-2.25f) \quad (4-1)$$

The crustal anomaly field was modeled as white noise at the earth's surface:  $0.083 \text{ (nT)}^2/(\text{cycle/rev})$  (Ref. 4). This modeling pertains to the vertical component of the field.

Table 4-1 illustrates the results of several runs of the survey simulation program. Results are shown for several

TABLE 4-1  
RMS RESIDUAL VERTICAL FIELD COMPONENT (nT) IN THE  
BAND  $3000 \text{ km} \leq \lambda_{\text{EAST}}, \lambda_{\text{NORTH}} \leq \lambda_s$

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$\lambda_s$ (km)	RAW FIELD	HIGH ORBIT (600 km)	INTERMEDIATE ORBIT (450 km)	INTERMEDIATE ORBIT (200 km)	LOW ORBIT (160 km)
100	221.4	218.4	216.1	193.3	176.1
300	75.9	66.8	58.6	6.1	2.4
500	45.5	28.0	13.8	0.6	0.3
700	32.2	8.3	2.2	0.2	0.1

different satellite altitudes, assuming a constant altitude and a track separation of  $1/2$  degree at the equator. In this case, the analysis is concerned with wavelengths between 3000 km and a variable short wavelength cutoff ( $\lambda_s$ ), which might be chosen for low-pass filtering of the data to remove short wavelength noise. The results of the different runs are expressed in terms of the rms residual power that would remain within the indicated wavelength band after the survey. This represents the magnitude of the error made if it were assumed that the output of the survey represented the crustal anomaly field.

Since the analysis includes the effects of upward or downward continuation, the residuals may be computed at any altitude. For this table, rather than computing the residuals at satellite altitude, they are all expressed at a common altitude of 1000 meters. This allows comparison of results in terms of a high altitude aeromagnetic survey, such as Project Magnet. The different columns of Table 4-1 quantify how the residuals decrease with decreasing satellite altitude. The rows illustrate the change in both the residuals and the raw field as the short wavelength cutoff is changed. For example, if wavelengths between 3000 and 700 km are considered, then the satellite survey at 600 km altitude would be able to map the



anomaly field to within 8.3 nT (from a total raw field power of 32.2 nT) at 1000 m. If wavelengths between 3000 km and 300 km are considered, then the residual is 67 nT (from a total raw field power of 76 nT).

5. UNRESOLVED QUESTIONS AND FUTURE DIRECTIONS

Unresolved Questions:

- The relationship between the computed magnetization parameter in ESMAP and the ambient crustal susceptibility is still not solved.
- Determination of the optimal dipole spacing requires a tradeoff: a smaller dipole spacing will ease the "ripple effect" but increase the noise in the anomaly map (Refs. 4,5), while a large spacing will increase the "ripple effect" while decreasing the noise. A one-degree spacing should substantially reduce the "ripple effect" while a two degree spacing will reduce the resulting noise in the magnetization and anomaly maps.

Future Directions:

- The methods and analysis thus far applied to the Broken Ridge will be expanded to the entire investigation area following the determination of the optimal dipole spacing and generation of an area-wide magnetic anomaly map. Specifically, further analysis will better constrain the apparent geologic difference between the eastern and western portions of the Broken Ridge, a difference suggested from the preliminary analysis in Chapter 1.
- We will consider the applicability of Poisson's relation which relates a derivative of the gravity potential with magnetic potential when both the density and magnetization are known and uniform. The magnetic potential field and crustal magnetization are estimated using ESMAP, the gravity potential is estimated from satellite altimetry data, and the crustal density structure is estimated from published geophysical surveys. Adding Poisson's relation overdetermines the system and may yield a method to further constrain certain geophysical parameters (e.g., density, susceptibility).

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